Modeling the Multi-body System Dynamics of a Flexible Solar Sail Spacecraft

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ABSTRACT

Solar sail propulsion systems enable a wide range of space missions that are not feasible with current propulsion technology. Hardware concepts and analytical methods have matured through ground development to the point that a flight validation mission is now realizable. Much attention has been given to modeling the structural dynamics of the constituent elements, but to date an integrated system level dynamics analysis has been lacking. Using a multi-body dynamics and control analysis tool called TREETOPS, the coupled dynamics of the sailcraft bus, sail membranes, flexible booms, and control system sensors and actuators of a representative solar sail spacecraft are investigated to assess system level dynamics and control issues. With this tool, scaling issues and parametric trade studies can be performed to study achievable performance, control authority requirements, and control/structure interaction assessments.

INTRODUCTION

Solar sail propulsion technology could potentially be the key that opens a door to fundamentally new classes of space science missions. By utilizing solar radiation to produce thrust, solar sails eliminate much of the launch mass associated with propellant needed for the life of a mission. Solar sails utilize the momentum imparted by reflected solar photons to generate a propulsive force.

Although the momentum imparted by individual photons is very slight, integrating the thrust force over large reflective areas can generate an appreciable force. Significant thrust performance can be achieved with solar sails by maximizing the sail size and reflective properties and minimizing the sailcraft mass, thus enabling missions that can not be achieved with conventional propulsion systems. Maximizing the sail area while minimizing the sailcraft mass is a significant engineering challenge. Innovative materials, manufacturing processes, deployment concepts, and modeling tools are necessary for realistic, operational solar sailcraft.

Stability and control of a solar sailcraft is a particularly difficult challenge. The structural dynamics of very large gossamer structures such as solar sails are notoriously difficult to model, being characterized by low frequency, closely spaced, and lightly damped fundamental modes of vibration. Once excited, these modes will induce slowly decaying, large scale deformations of the sail structure. Uncertain structural deformations, both static and dynamic, result in uncertainty and variability in the thrust vector magnitude and direction which may degrade system performance and potentially destabilize the sailcraft attitude dynamics. Moreover, uncertainties in material properties compound the thrust vector uncertainty. The degree to which the system performance and stability are degraded is a function of the robustness of the control system and knowledge of the system dynamics.

The purpose of this study is to develop a closed-loop system level dynamics analysis tool to provide insight into the coupled dynamics of the sailcraft bus, sail membranes, flexible booms, and control

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system sensors and actuators of a solar sail spacecraft. Using the multi-body dynamics and control analysis tool called TREETOPS, this study models the dynamic response of a representative solar sail spacecraft to investigate the coupled flexible body dynamics and feedback control systems.

SOLAR SAIL MODEL DESCRIPTION

TREETOPS implements Kane's equations to model multiple interconnected structural subsystems, or "bodies," which may be either flexible or rigid. The interconnections between subsystem bodies are defined by "hinges" with allow up to six degrees of freedom (DOF) relative motion as well as interface dynamics such as linear spring stiffness and damping. A suite of control system sensors and actuators can be attached at various locations on any body with PID, state-space, and user-defined feedback control systems. Thus TREETOPS is a powerful tool for modeling the closed loop dynamics of structural systems. In this study, the sailcraft system described in [2] is used to demonstrate the modeling and analysis capabilities of TREETOPS applied to solar sail spacecraft. Future studies will build on this model for control system architecture trade studies and dynamics analysis for other sailcraft system concept studies.

The solar sail system architecture for this study is based on a four-quadrant square sailcraft. Most control system architectures for solar sailcraft vary either the center of mass location or the center of pressure location (the resultant of the net solar radiation pressure force) to null the bias torques and generate maneuvering torques. For the architecture modeled in this study, the sail attitude control system (SACS) utilizes masses that translate along the booms for pitch and yaw control (rotation about booms) and sail panel rotation for roll control (rotation about vector normal to plane defined by undeformed booms). Sail panel rotation is accomplished by rotating "roll spreader bars" (RSB) that are attached to the end of the booms. As shown in Figure 1, the TREETOPS model of the solar sail system has fifteen bodies: one body for the spacecraft bus (S/C), four flexible booms, four solar sail membrane quadrants, four roll spreader bars, and two moving masses. All of the bodies are connected by using TREETOPS hinges with the appropriate degree of freedoms (DOF) and tuned linear spring devices.

SAILCRAFT STRUCTURAL MODEL

To simplify the model development for first generation sailcraft model, the sail membranes are modeled as rigid bodies with the correct mass and inertia. By tuning the hinge stiffness at the interconnections between the sail quadrants and booms, the first mode of the membrane dynamics can be modeled and the dynamic coupling between booms and membranes can be accounted for. Future versions can replace the rigid membrane quadrants with flexible dynamics from NASTRAN models of the sail quadrants. In the current sailcraft model, the solar radiation pressure is represented as a force applied normal to the membrane at the center of mass (CM) of each quadrant. This force is assumed to be maximum when the membrane is normal to the Sun and varying according to the change of angle between the membrane normal unit vector and the Sun normal unit vector. This angle change is measured using TREETOPS Sun sensor located on the CM of membrane. A TREETOPS "User Defined Continuous Controller Subroutine" (USCC) is used to implement the solar radiation pressure model which can be readily enhanced with higher fidelity radiation pressure models in future revisions.

The solar sail system was modeled as fifteen bodies and all bodies are connected using TREETOPS hinges according to the TREETOPS tree topology. The spacecraft bus (S/C) is defined by Body #1 and linked to Hinge #1 with six degrees of freedom (three rotational and three translational) with respect to the origin of the inertial coordinate system. The spacecraft bus is modeled as a rigid body with the proper mass and moment of inertias. For Body #1, nine nodal points are chosen to represent the

center of mass and origin of local coordinate system of Body #1, four boom attaching points, and four solar sail membrane attaching points.

Boom flexibility can be modeled in one of two ways. The simplest way is to use a rigid body and connecting a hinge with rotational DOFs such that the hinge stiffness and damping are chosen to represent the dominant bending mode. A higher fidelity approach models each boom as a flexible body by importing the modal properties (mode shapes and slopes, generalized mass and generalized stiffness) of the boom obtained from a NASTRAN normal modes analysis. Both approaches were implemented in this study and the two resulting TREETOPS models were compared and validated against each other. The results presented herein are obtained utilizing the modal properties of first in-plane bending, out-of-plane bending, and torsion modes that were calculated using NASTRAN normal modes analysis of each boom with fixed-free boundary conditions.

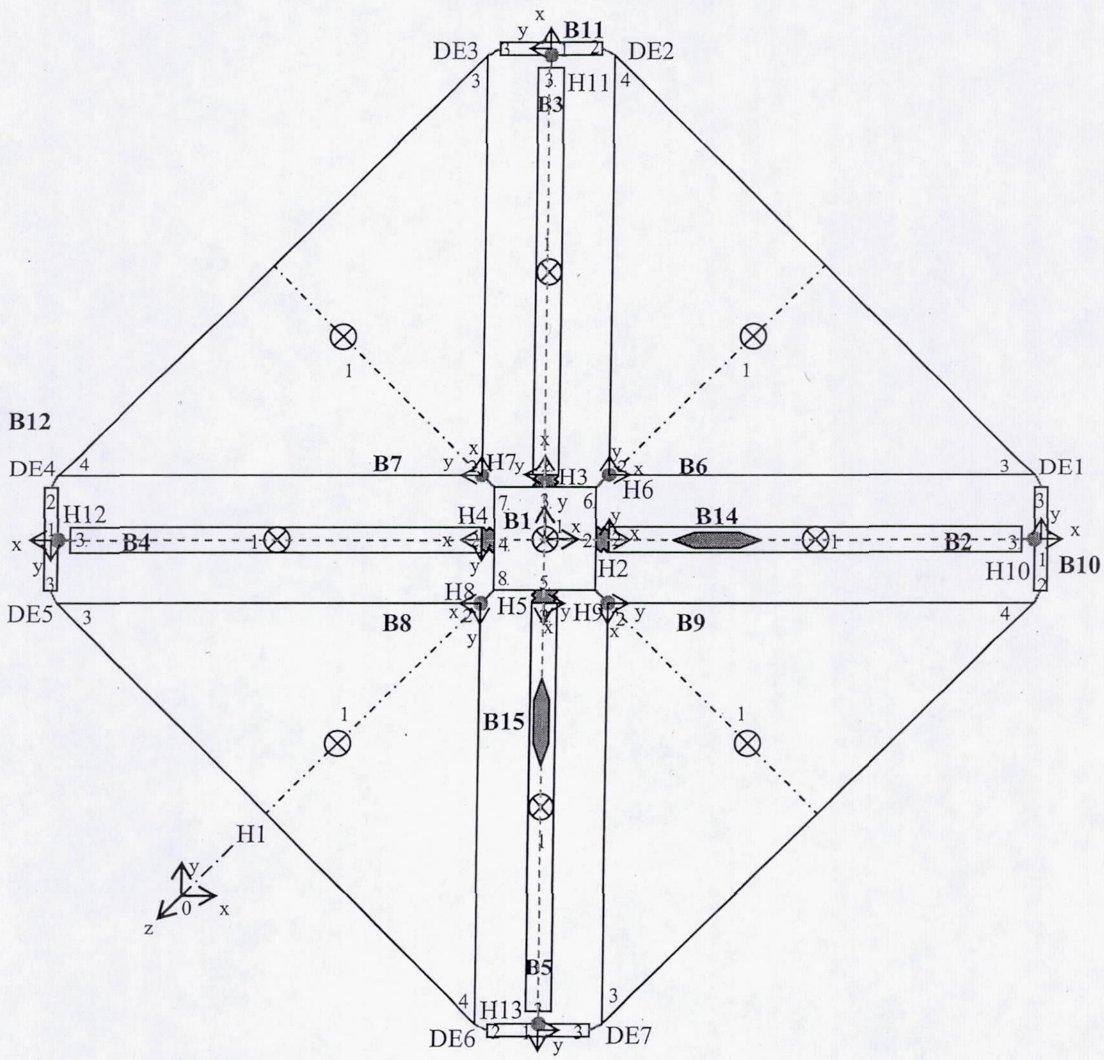

Figure 1: Configuration of TREETOPS Solar Sail Model

SAIL ATTITUDE CONTROL SYSTEM MODEL

Sailcraft are unique in that the attitude dynamics are coupled with the orbit dynamics since the thrust vector is pointed by controlling the attitude of the sailcraft. Thus to track a reference trajectory, thrust vector commands are converted into the appropriate attitude commands and the attitude control system generates the torques required to maneuver the vehicle to the commanded attitude. For this TREETOPS solar sail spacecraft model, the SACS generates control torques in two axes by varying the center of mass location and hence the moment arm of the resultant solar radiation pressure force. Two point masses are modeled which translate along the x-axis and y-axis booms to generate pitch and yaw torques. For roll attitude control, four roll spreader bars are modeled as individual rigid bodies attached to the end of each boom, each with one rotational DOF about the boom longitudinal axis.

The required torques for the roll, pitch and yaw maneuvers of the spacecraft are calculated using a simple Proportional-Integral-Derivative (PID) control implemented in the built-in TREETOPS continuous block diagram controller (CBDC) module. The rotational angle commands of the RSBs are derived from the geometric and kinematic relationship between the solar sail membrane and the RSB, which is based on the required torque for the spacecraft roll maneuver. Similarly, the translational movement commands of the moving masses are derived from the required torques for the spacecraft pitch and yaw maneuvers. These procedures are implemented in the USCC. The motions of the RSB and moving masses are controlled to follow the above commands using a PID actuator control loop for each actuator.

Several TREETOPS sensors are modeled to obtain the rotational angles of all bodies for the TREETOPS simulation. Four TREETOPS Integrating Gyro sensors are mounted on the CM of four solar sail membranes in order to measure the rotational angles in inertial frame about the rotation axis through the center line. Four TREETOPS Resolver sensors are used to measure the rotational angles of four roll spreader bars. These angles are used as feedback input for PID controls of the RSB rotation. Four TREETOPS Sun Sensors are mounted on the CM of four solar sail membranes to measure the angles between the Sun line-of-sight (LOS) vector and the normal vectors to the membranes. The angles obtained from the sun sensors are used to calculate the solar pressure forces. Three TREETOPS Resolver sensors measure three rotational angles of the solar sail spacecraft about x-, y-, and z-axes. These angles are used as feedback input for PID controls of the spacecraft maneuver.

TREETOPS built-in actuators are convenient ways to apply forces and torques to mutilbody structural system by automatically handling the complex interface between actuators and the structure. Four TREETOPS Reaction Jet actuators are mounted on the CM of the membrane bodies to generate the solar radiation force to be exerted on four solar sail membranes. The inputs to these actuators are the sun radiation forces that are proportional to the cosine angle between the membrane normal vector and the Sun LOS. Four TREETOPS Torque Motor actuators are mounted on the hinges that attach the membrane quadrants to the boom tips to apply control torques that drive the RSB to the commanded angle. Two TREETOPS Reaction Jet actuators are mounted on the translating mass bodies in order to drive the masses to the commanded position. Three TREETOPS Moment Actuators are mounted on the CM of the spacecraft bus to generate disturbance torques for control system performance evaluation.

The sailcraft system modeled in this manner embodies the coupled flexible body dynamics and closed loop control system architecture of a representative solar sail spacecraft. The next section describes the simulation results obtained from this TREETOPS model with representative sailcraft properties. In all, this model embodies six distinct PID control loops: one for each of pitch, yaw, and roll actuator controllers and one for each of the three vehicle attitude control loops.No attempt was made to

tune or optimize the performance or margins of the various control systems in this model; rather, this analysis simply demonstrates the ability of the TREETOPS model to adequately address the key issues associated with the dynamics and control of solar sail spacecraft.

SOLAR SAIL SIMULATION RESULTS

The TREETOPS model was tested by simulating closed loop attitude control of the solar sail spacecraft. Three test cases were run with a one degree attitude step commands in the pitch, yaw, and roll axes, respectively. Vehicle rotations about the x-axis are generated by commanding the control mass to translate along the y-axis (moving the center of pressure and generating a torque about the x-axis). Likewise, rotations about the y-axis are accomplished with the translating mass along the x-axis.

For the first test case a commanded Pitch of one degree was input into the simulation. The attitude control law then commanded the corresponding translation of a moving mass to produce the needed maneuver. In Figure 3, the translation of the moving mass required for a 1 degree pitch is plotted.

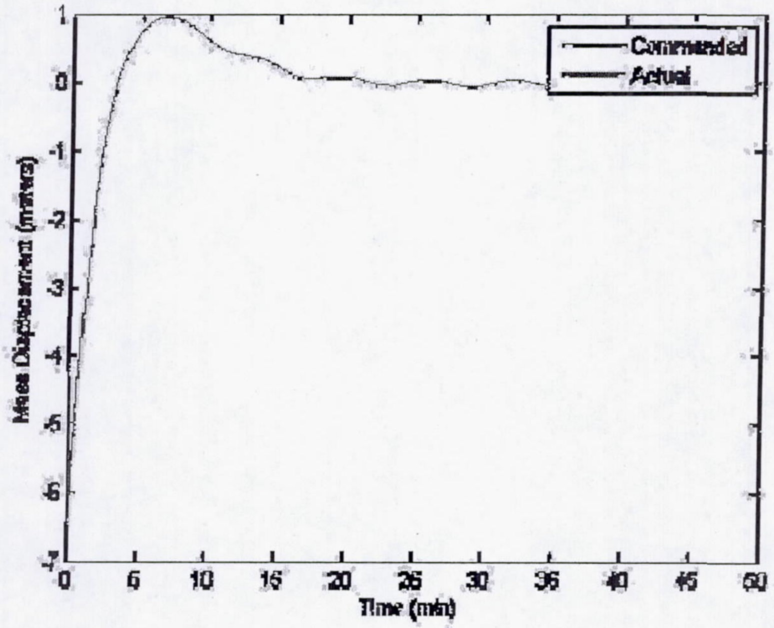

Figure 3: Body 16 (Moving Mass) Displacement vs. Time

In Figure 4, the commanded value for pitch is plotted with the actual pitch of the Solar Sail. As can be seen, the simulation was able to successfully to demonstrate a Pitch maneuver using translating masses. Again, the time response was not appreciably tuned since the objective was not control design as much as demonstrating correct control system implementation.

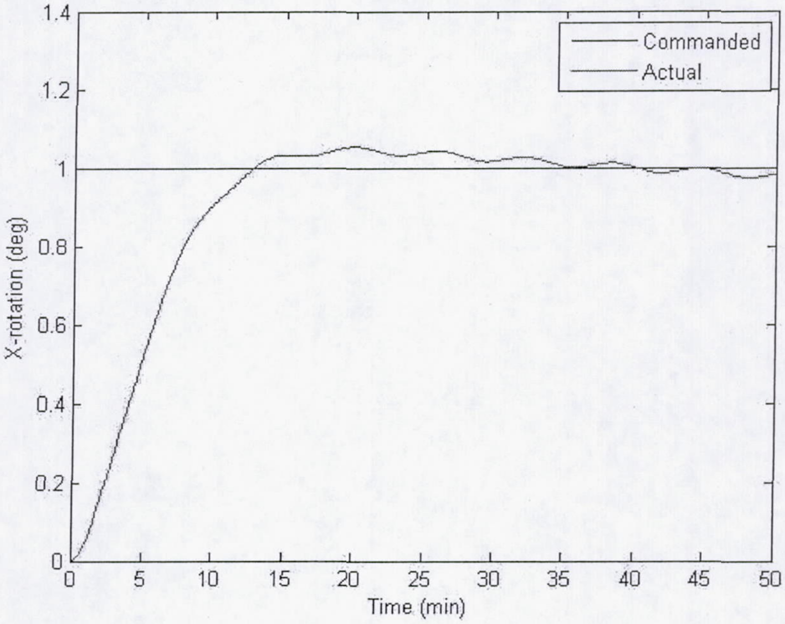

Figure 4: X-Body Rotation vs. Time

For the second case, a roll maneuver was performed by commanding the translating mass. Figure 5 shows the mass displacement compared to the corresponding commanded value.

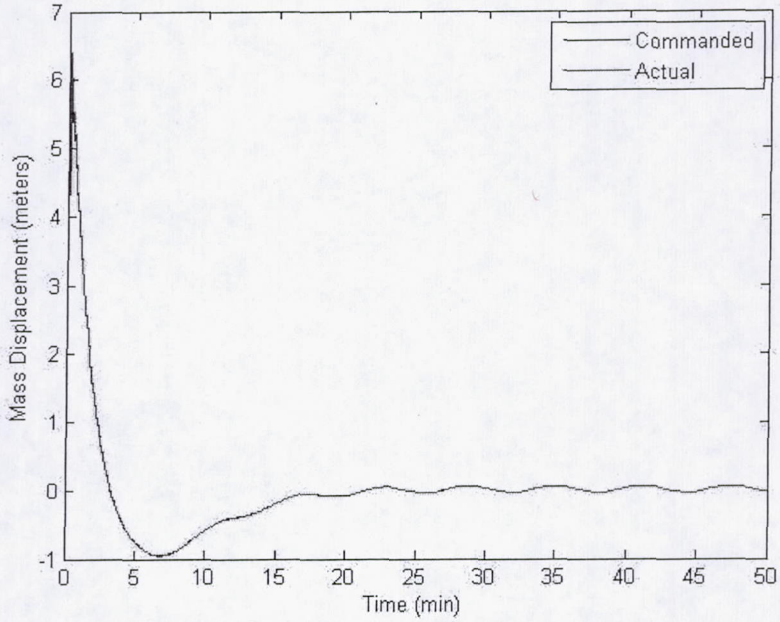

Figure 5: Body 14 (Moving Mass) Displacement vs. Time

In Figure 6, the resulting rotation of the body is plotted with its corresponding commanded value. The results of the Roll maneuver match the results of the Pitch maneuver, which is to be expected because the processes behind the maneuvers are identical.

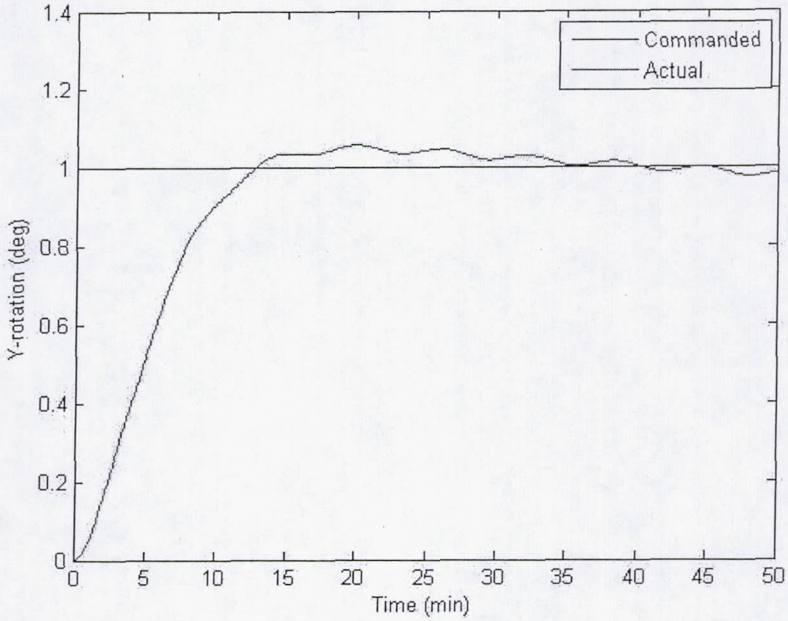

Figure 6: Y Body Rotation vs. Time

For the Roll maneuver, the roll spreader bars are commanded to rotate the sail quadrants and generate a component of the solar radiation pressure in the plane defined by the sailcraft booms. This in-plane force produces a roll torque about the vehicle center of mass. In Figure 7, the rotation of the torque bars are plotted against their commanded value for a roll maneuver of 1 degree. The corresponding sail rotation is shown in Figure 8 and the resulting yaw of the solar sail system is shown in Figure 9. As shown, the yaw of the sailcraft is converging toward the commanded value.

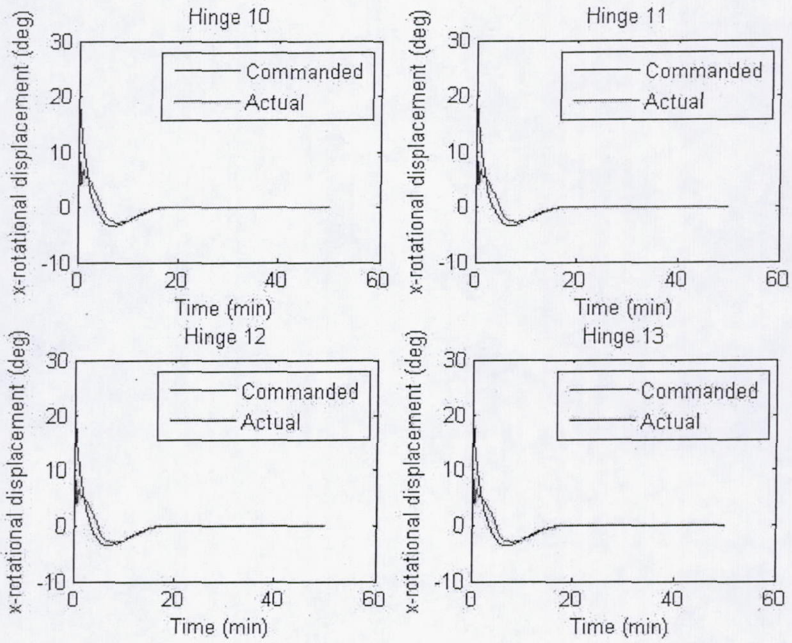

Figure 7: RSB Rotation vs. Time

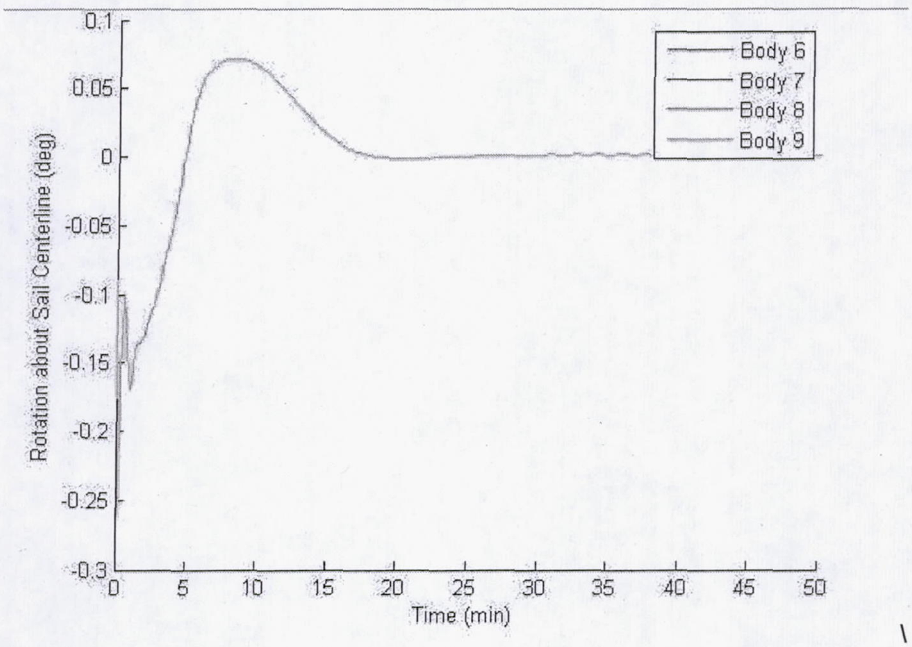

Figure 8: Sail Rotation vs. Time

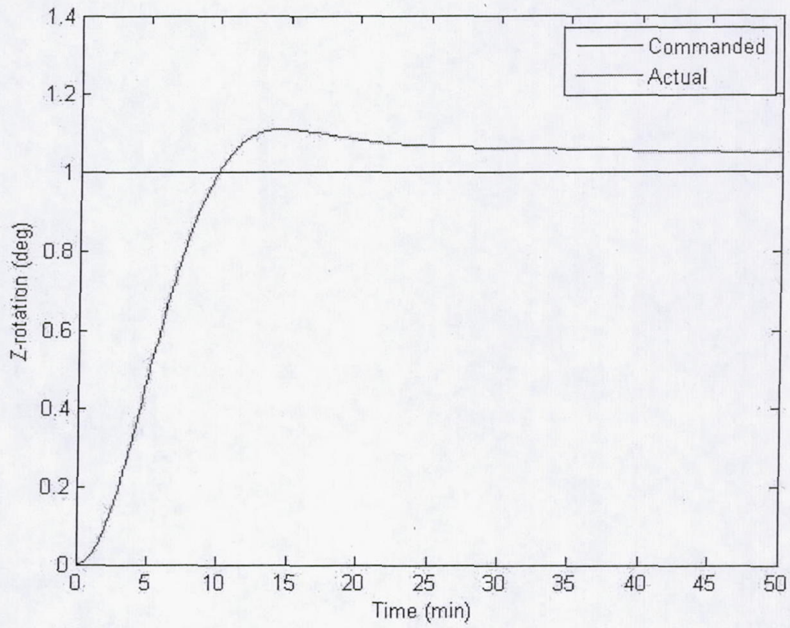

Figure 9: Z Body Rotation vs. Time

CONCLUSIONS

The purpose of this study was to develop a simulation that would model the dynamics and control of a solar sail spacecraft system and accommodate the interactions between structural dynamics and control systems. The simulation currently embodies the coupled dynamic interaction between flexible booms and the first bending mode of each sail quadrant. Local controllers and subsystem bodies implement the dynamic response and control inputs of the translating masses and tip spreader bars. This same approach and concepts can readily implement other concepts such as articulating tip vanes and gimbaled offset masses. Further developments of the sailcraft model will account for more realistic solar radiation pressure models and disturbance torques. With other sail system architectures implemented, this tool will be useful for control architecture trade studies and performance analysis.

ACKNOWLEDGEMENTS

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REFERENCES

[1] "User's Manual for TREETOPS, A Control System Simulation for Structures With a Tree Topology," NASA Contract NAS-36287, Marshall Space Flight Center, April 1990.

[2] Bong Wie, David Murphy, Michael Paluszek, and Stephanie Thomas, "Robust Attitude Control Systems Design for Solar Sail Spacecraft", AIAA 2004-5010, Presented to the AIAA GNC Conference, August 16-19, 2004, Providence, RI

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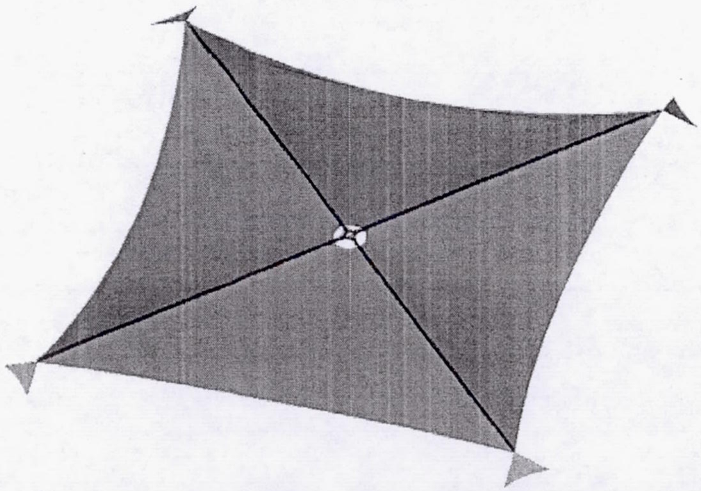
To mature the TRL of solar sail propulsion systems will require advancements in modeling and controlling the dynamics of large flexible space structures.

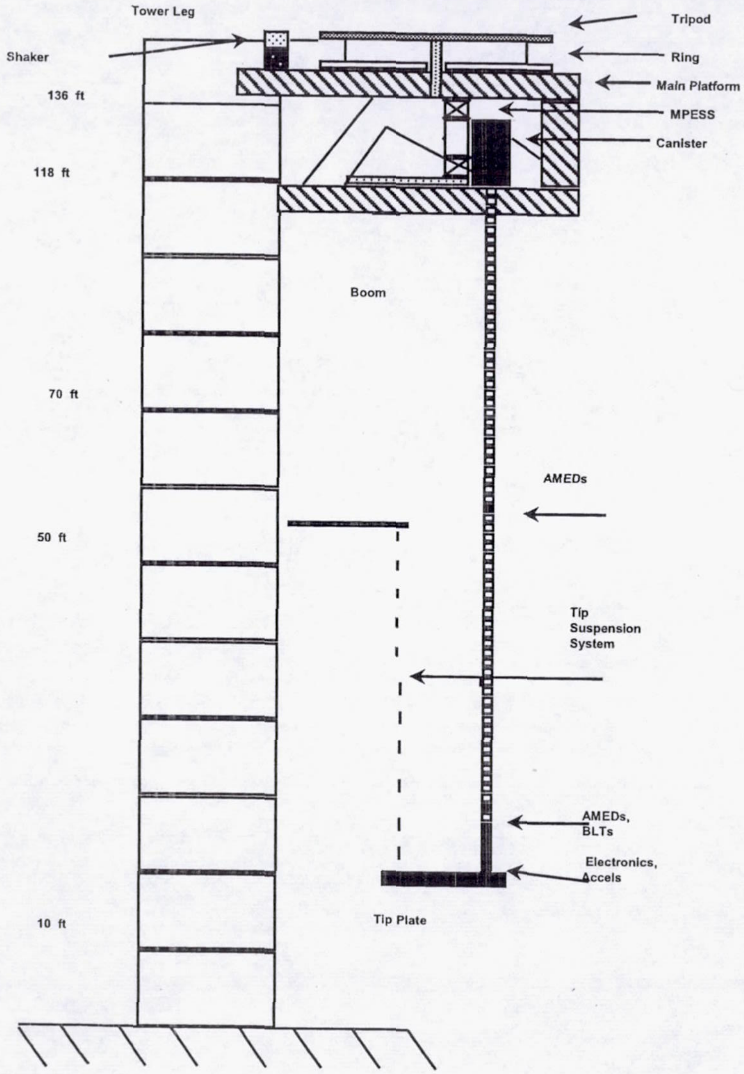
Sailcraft Modeling & Control

Solar Sailcraft present a significant dynamics and control challenge

- Low frequency modes of vibration
- Lightly damped modes
- Closely spaced modes
- Coupled system modes
- Potential Control-Structure Interaction



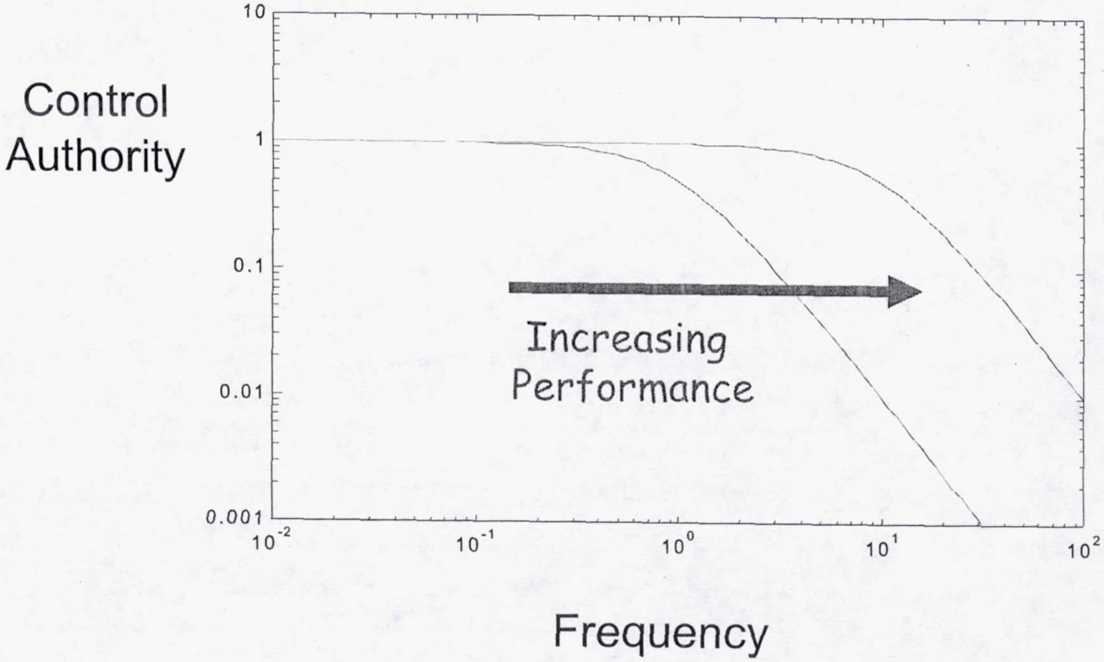
Characteristics of Flexible Space Structures



System ID Freq (Hz)	System ID Damp(%)	Modal Test Freq (Hz)	Finite Element Freq (Hz)	Mode Description
0.118	0.506	0.112	0.08	Y 1st bending
0.119	6.48	0.120	0.09	X 1st bending
0.215	0.904	0.210	0.16	1st Torsion
0.325	57.3			
0.535	1.07	0.520	0.56	X 2nd bending
0.554	0.604	0.530	0.58	Y 2nd bending
0.953	3.60			
1.214	38.8	1.391	1.23	X 3rd bending
1.539	17.7			
1.771	3.15			
1.872	2.76	1.868	1.82	Y 3rd bending
2.061	13.2			
2.839	9.45	2.802	2.73	Y 4th bending
3.073	3.58	2.995	3.28	X 4th bending

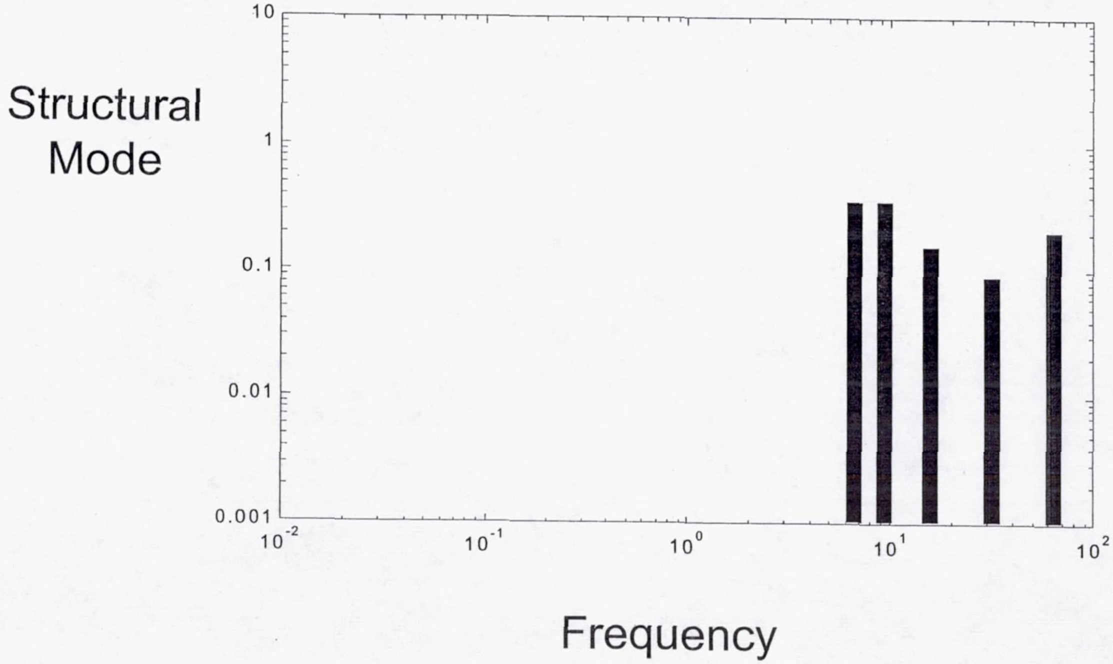
Sailcraft Modeling & Control

First consider the control system

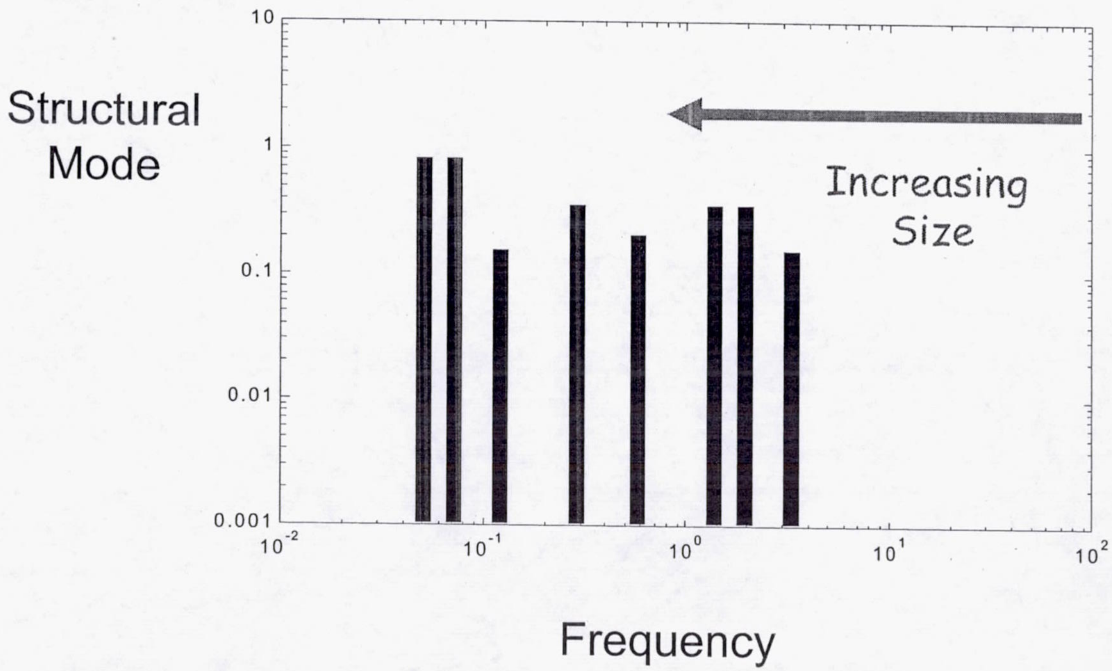


Sailcraft Modeling & Control

Now the structural dynamics



Sailcraft Modeling & Control

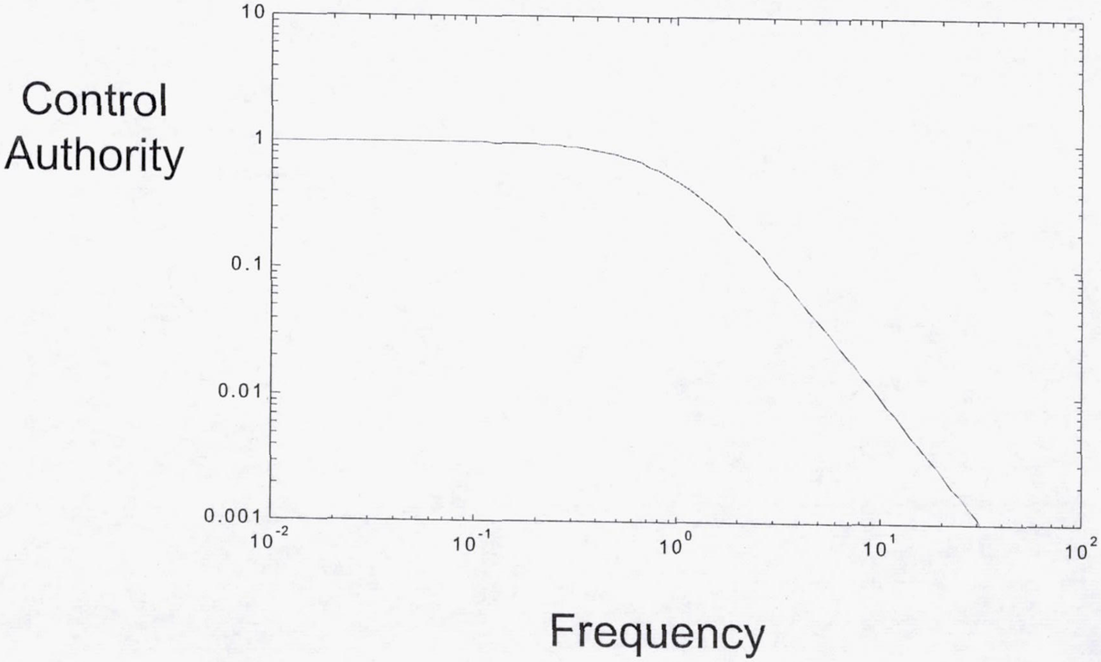


Sailcraft Modeling & Control

Now let's consider some cases...

Sailcraft Modeling & Control

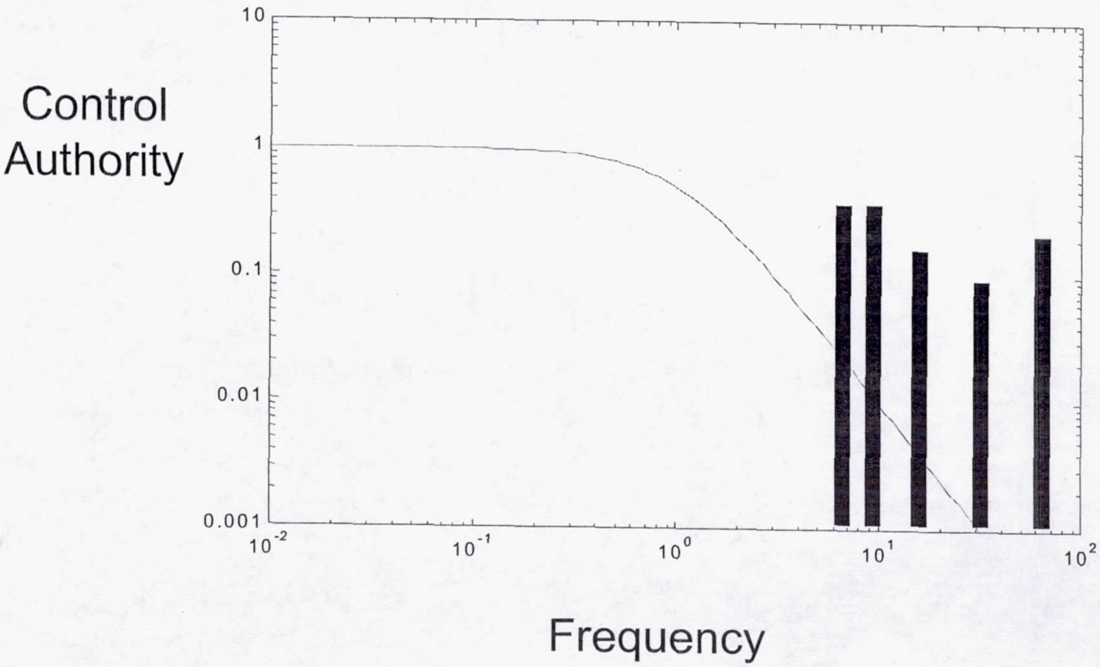
First is the typical flight vehicle case



Low Performance/Stiff Structure

Sailcraft Modeling & Control

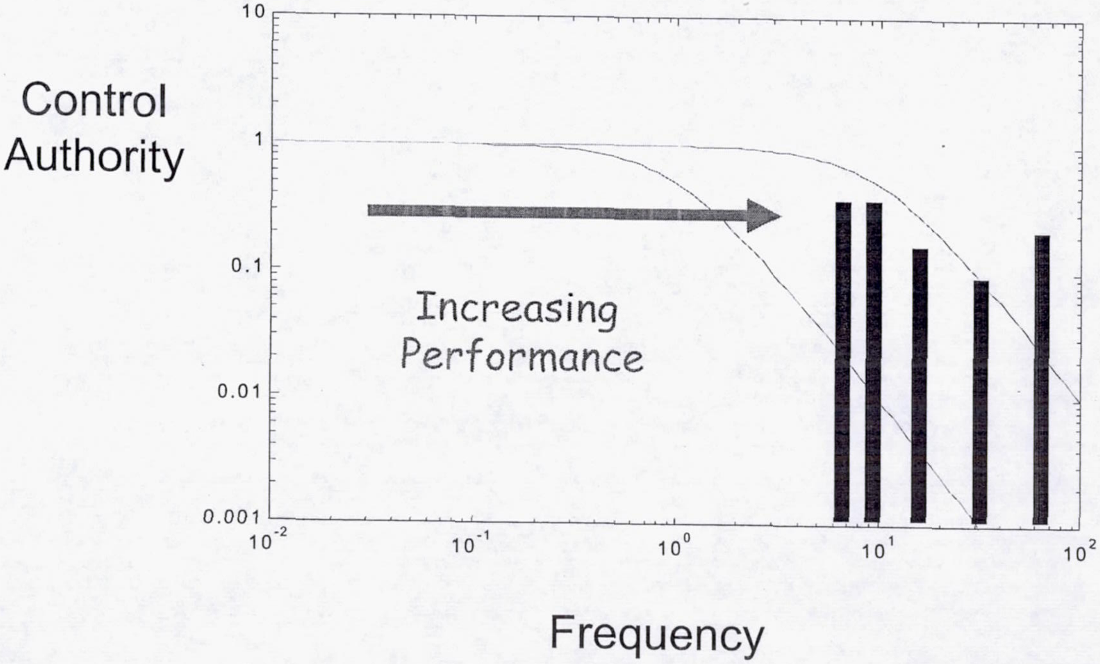
Flex modes are not excited by the controller



Low Performance/Stiff Structure

Sailcraft Modeling & Control

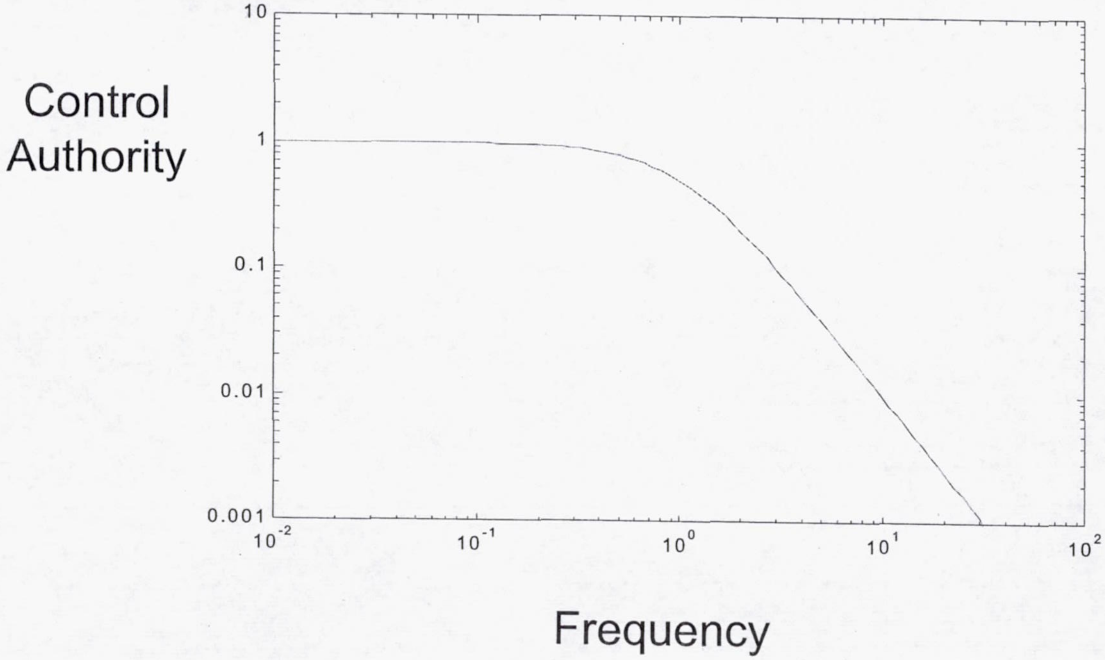
But if the required performance increases



The controller interacts with the structural dynamics

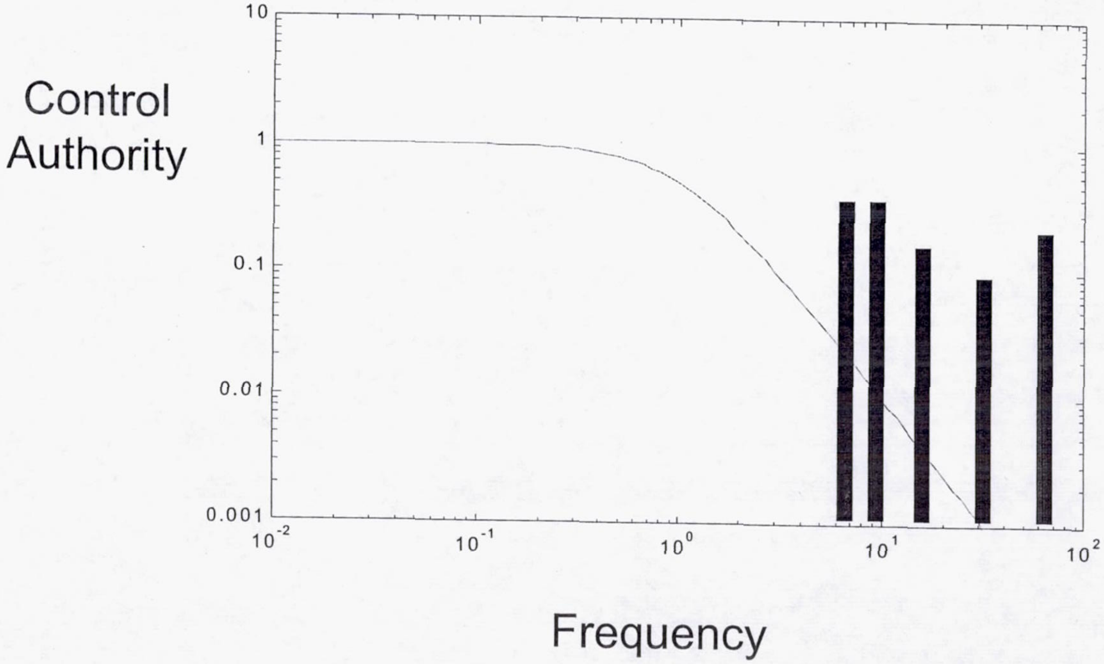
Sailcraft Modeling & Control

Return to the Low Performance Controller



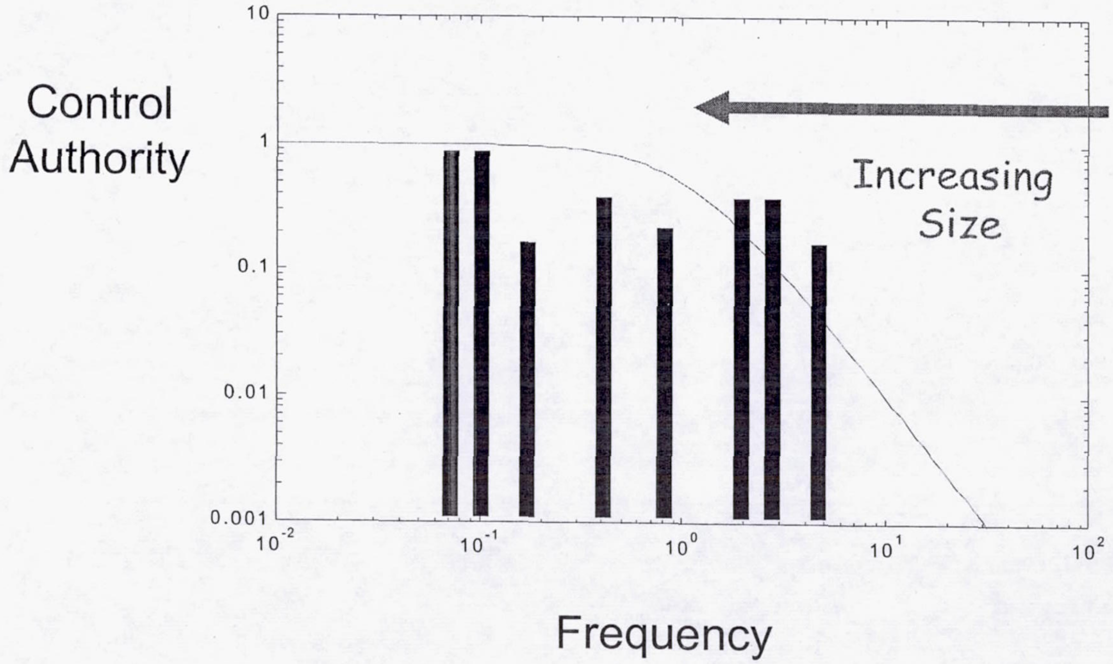
Sailcraft Modeling & Control

Add modes from a stiff structure



Sailcraft Modeling & Control

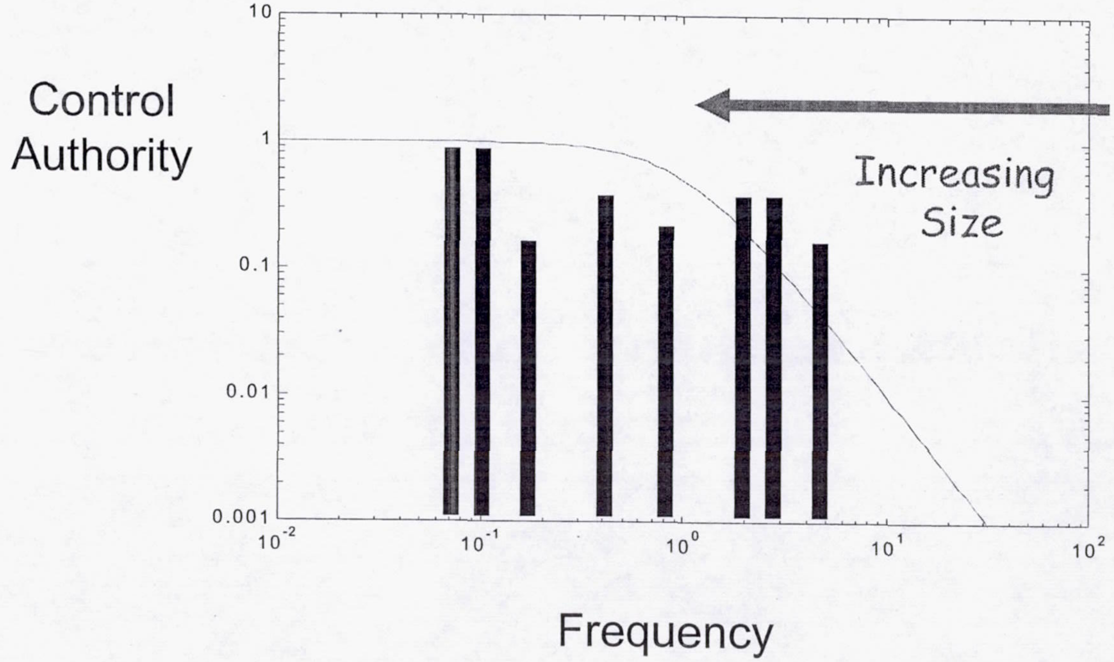
Now consider the flexible structure case



Again the controller interacts with the structural dynamics

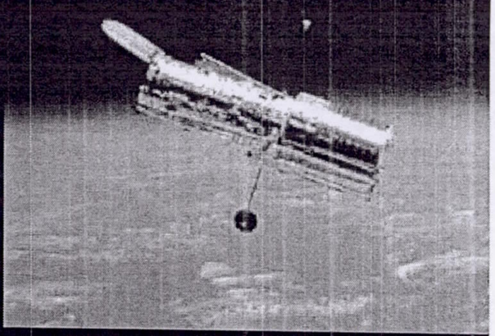
Sailcraft Modeling & Control

Low Performance/Flexible Structure

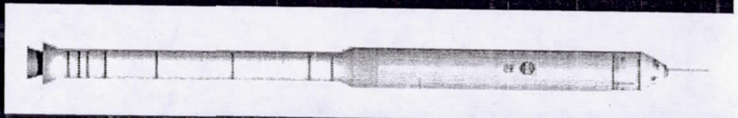


CSI can potentially occur whenever the control bandwidth encompasses structural modes

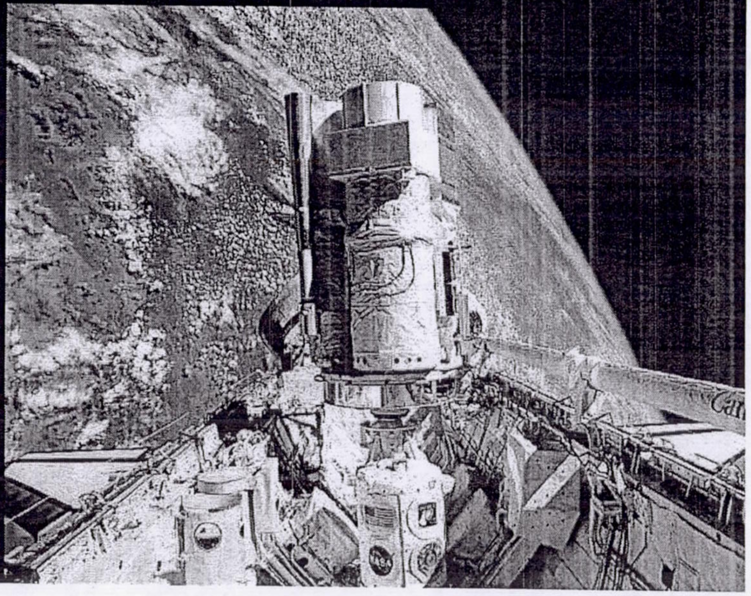
What is TREETOPS?



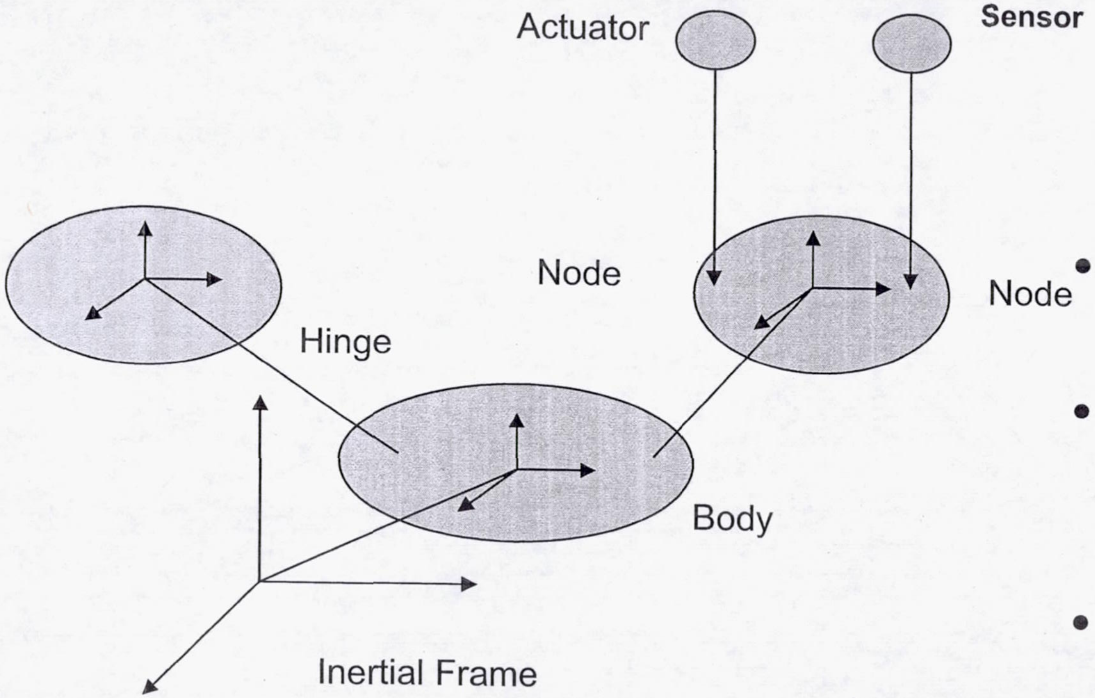
- An integrated simulation program for analyzing closed-loop flexible multi-body systems with constraints



- Developed by Dynacs for NASA Marshall Space Flight Center.
- TREETOPS and its derivatives are a benchmark for flexible multi-body system simulations in the aerospace industry.

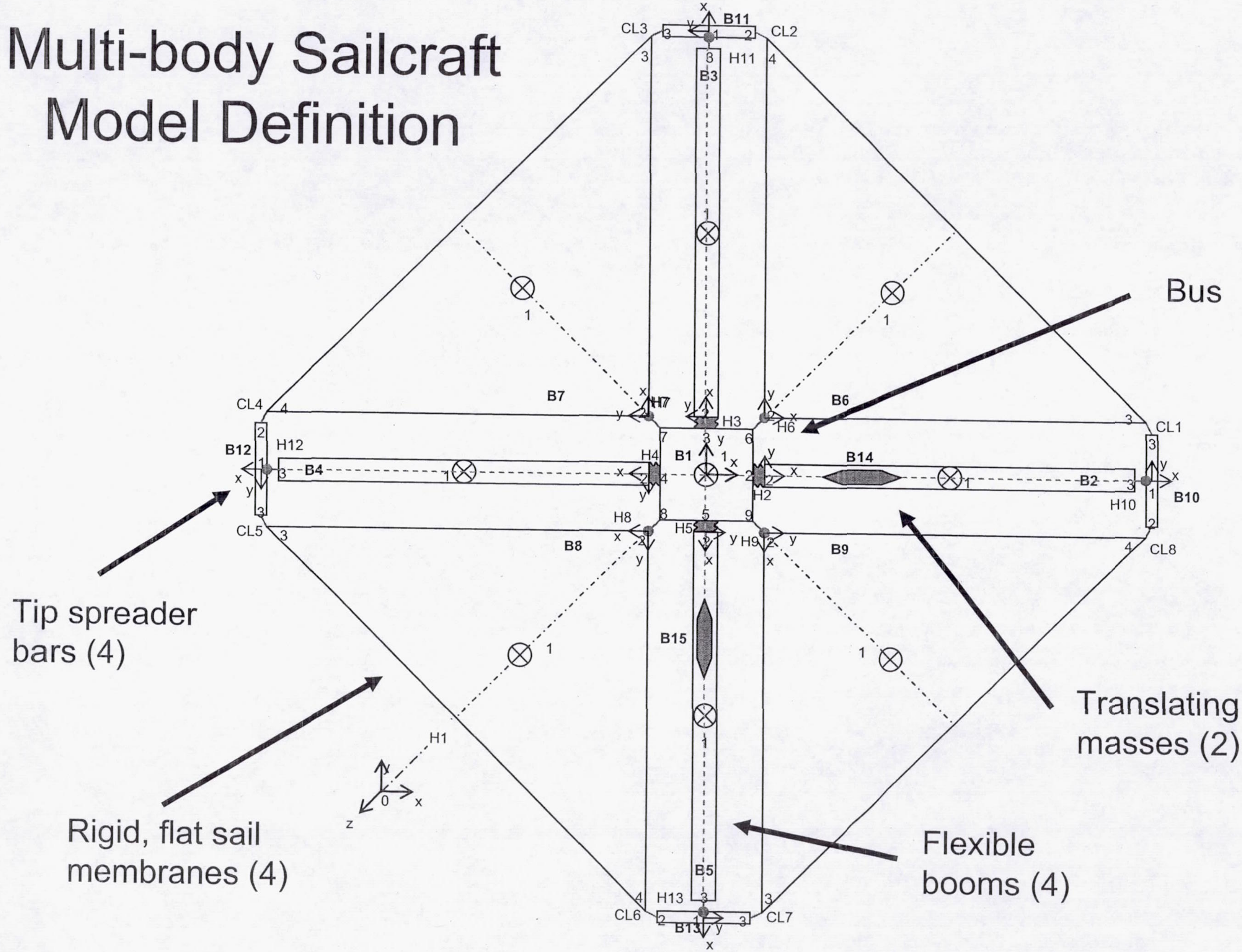


Generic Treetops Architecture

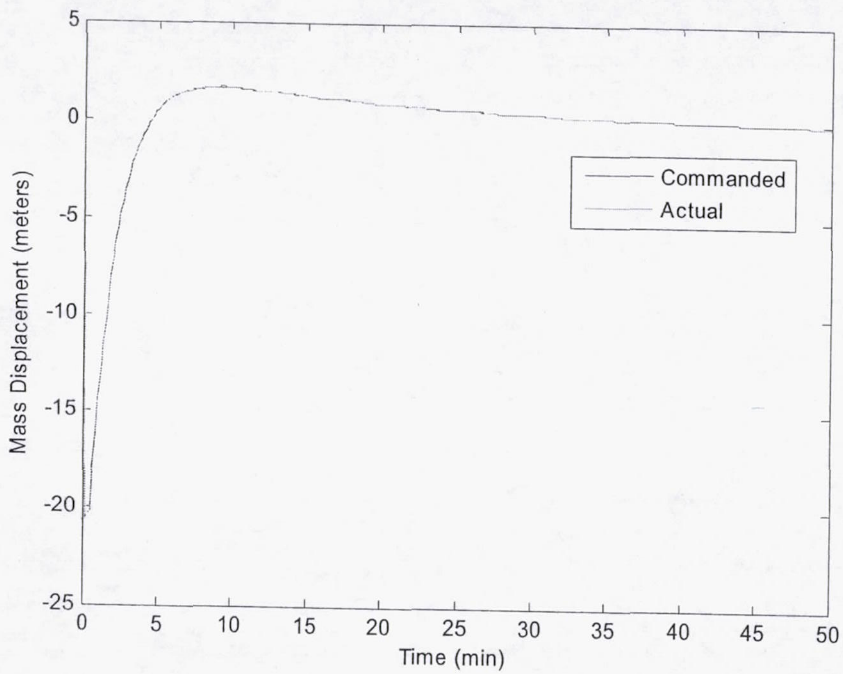


- Models systems in a tree topology
- Interconnected bodies, sensors, and actuators
- Bodies modeled as rigid or flexible

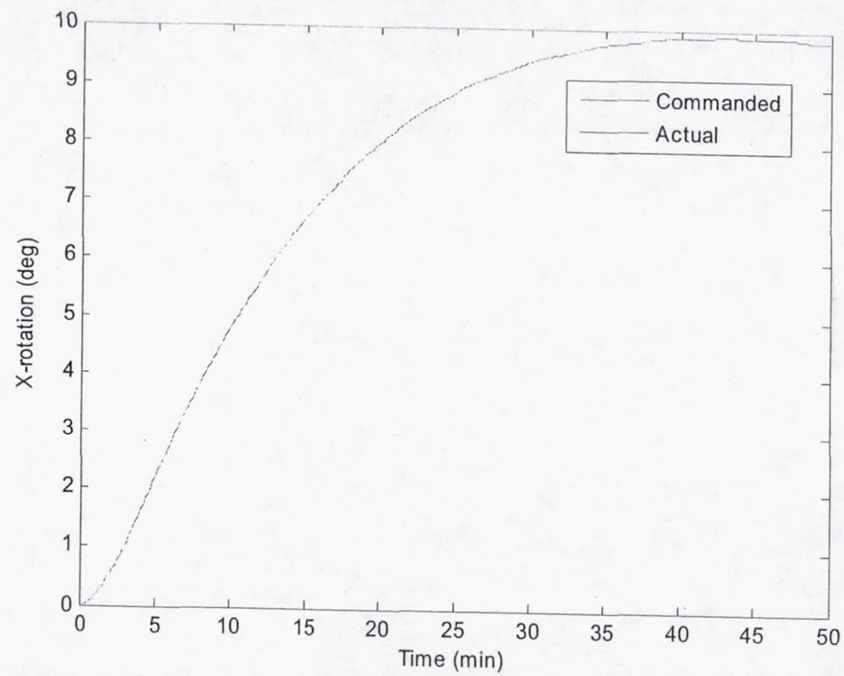
Multi-body Sailcraft Model Definition



Closed-Loop Pitch Maneuver



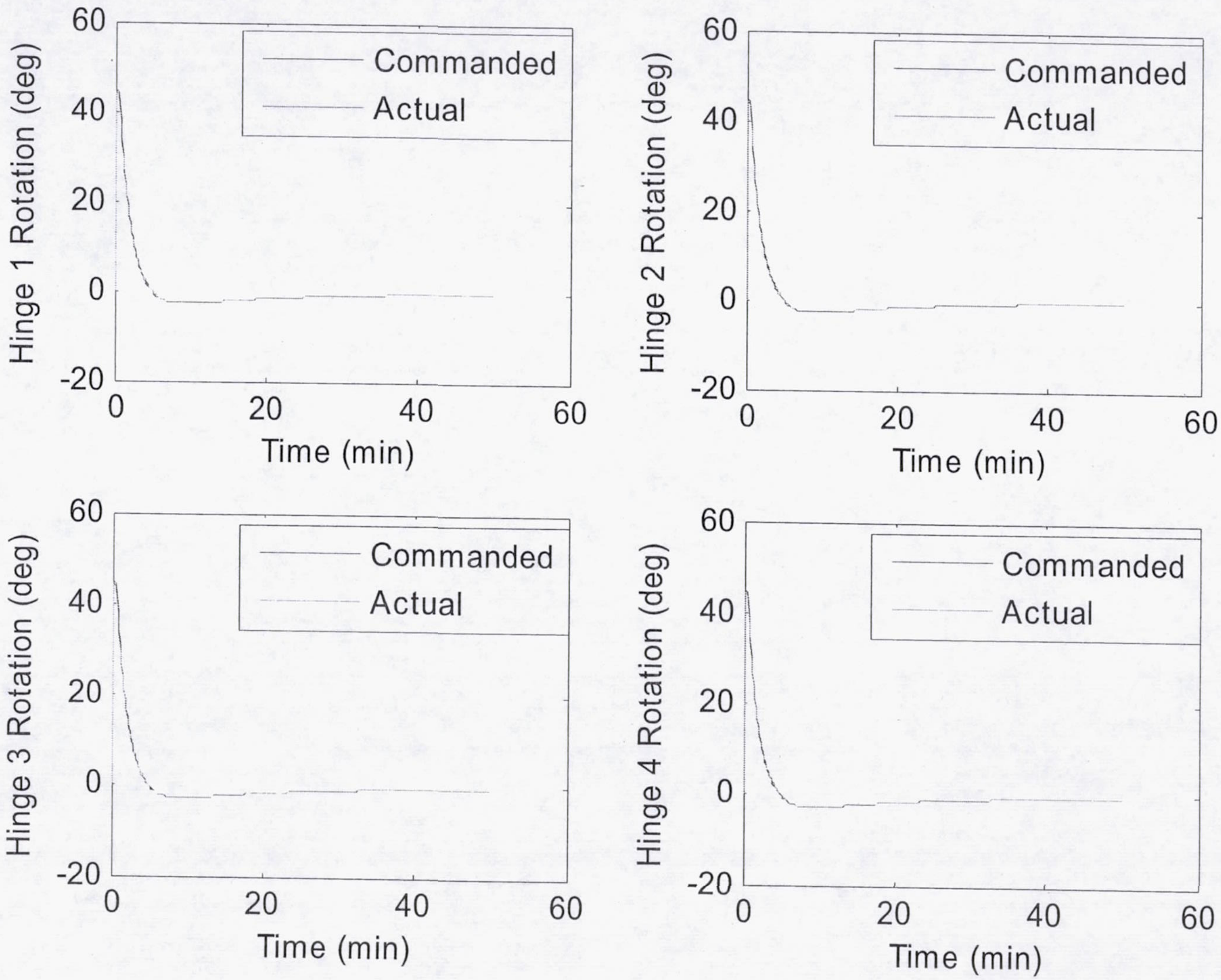
Y-Axis Moving Mass Displacement vs. Time



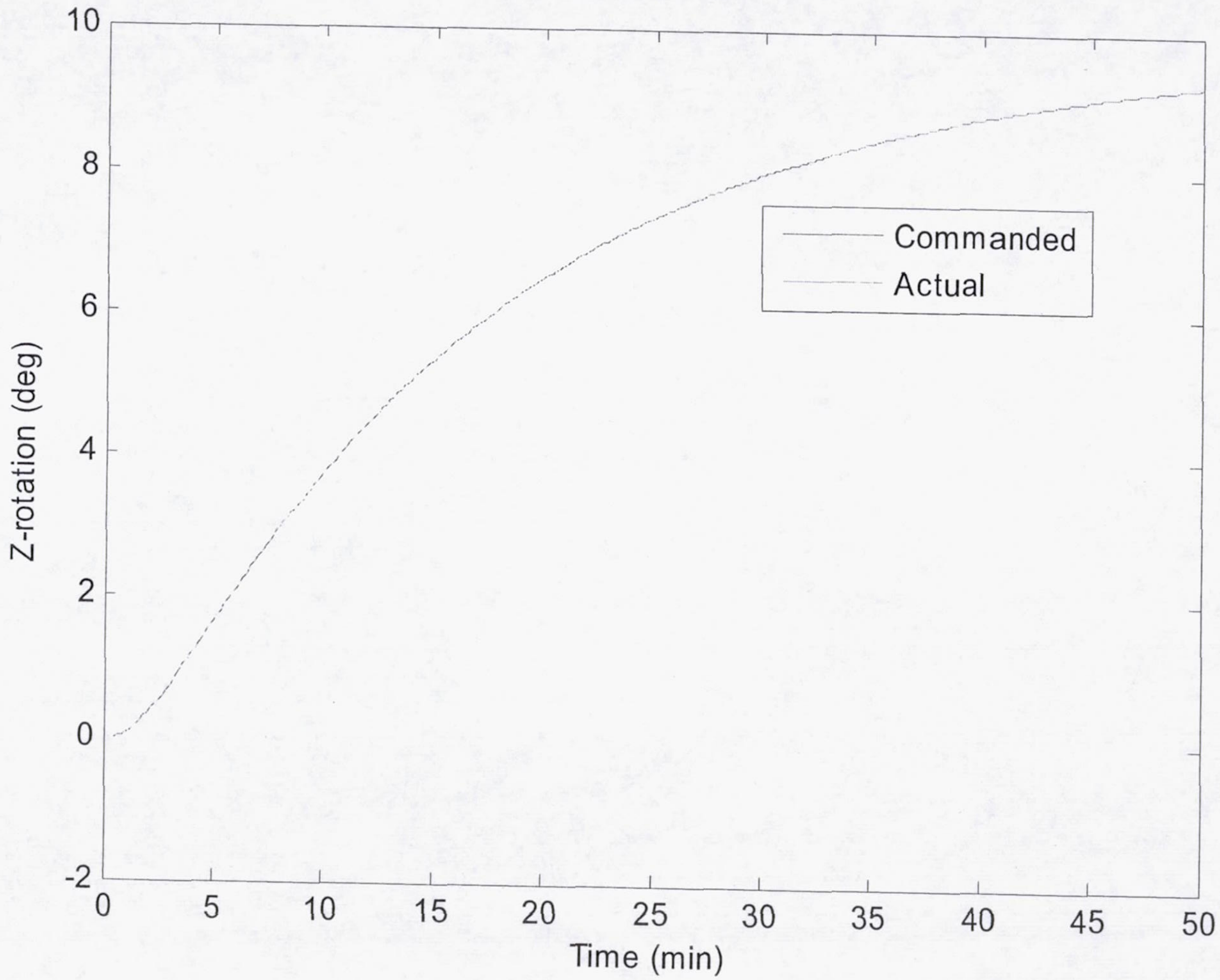
Pitch Response

Yaw Response is identical due to decoupling & symmetry

Closed-Loop Roll Maneuver



Closed-Loop Roll Maneuver



TREETOPS Modeling Summary

- Multibody dynamics
- Flexible bodies (booms only now)
- Actuator dynamics
- Closed loop attitude control

$\Rightarrow$ *Readily reconfigurable to other sailcraft configurations and control architectures*